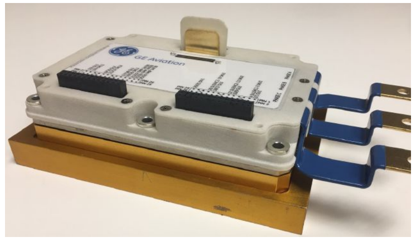
High Power Density Dual-Rotor Permanent Magnet Motor with Integrated Cooling and Drive for Aircraft Propulsion

Dr. Philippe Masson, Advanced Magnet Lab (AML)

PM-360™



Power Electronics

*Innovative **permanent magnet manufacturing process** for cost effective better than "Halbach arrays" magnets and **compact SiC modules with Intelligent Active Gate Driver** enabling **high power density electric drivetrains**.*

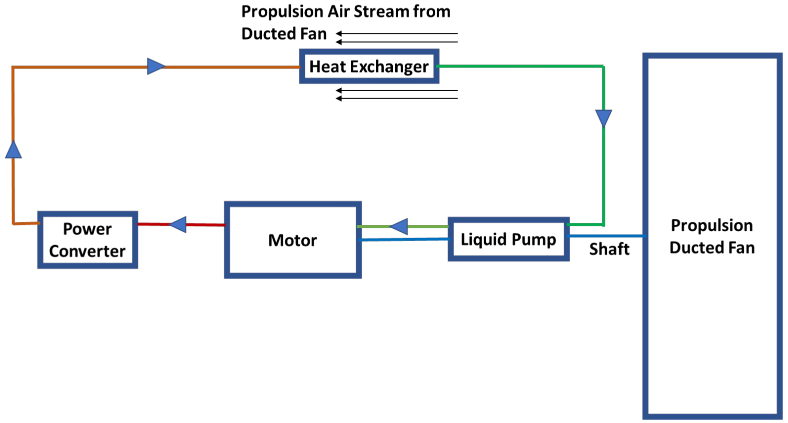
REEACH / ASCEND / CABLES
Annual Program Review Meeting
June 28-30, 2022

Brief ASCEND Project Overview

Fed. funding:	$1.8M
Length	42 mo.

- *Initial activities focused on superconducting machines for Turbo-Electric Propulsion (NASA)*
- *Permanent magnet motors can reach high specific torque/power with **Halbach arrays** (20-30 Nm/kg)*
  - *Need new technology to produce "**better**" and **less expensive Halbach arrays***
    - *Apply novel permanent magnet manufacture process (**PM-360**™) for rotor and AML's electro-magnet technology for stator*
  - *Need **effective heat removal** in the stator*
    - *Apply AML's "**transparent coil**" technology to stators*
  - *Need **high power density motor drive***
    - *Reached out to Prof. Li who is a SiC power electronics expert at FSU who accepted to join the project*

- Enabling features of high-power density drivetrain
  - **Dual-Rotor** Radial Flux Motor Configuration
    - AML **PM-360**™ – Continuously Changing Magnetization
    - AML **"transparent" stator winding** with direct cooling
  - FSU-CAPS **SiC power converters**
  - **Shared cooling loop** with heat rejection in propulsion stream



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CHANGING WHAT'S POSSIBLE

Brief ASCEND Project Overview

Fed. funding:	$1.8M
Length	42 mo.

Team member	Location	Role in project
Advanced Magnet Lab	Melbourne, FL	System level design space exploration, motor design and manufacturing, thermal management design and manufacturing, system integration.
Florida State University	Tallahassee, FL	Motor Drive design, optimization, manufacturing and testing

Project leaders

- *Dr. Philippe Masson, AML CTO*
  - *Analysis-led design*
  - *Electro-mechanical devices design and optimization*
  - *Multiphysics simulations*

AML

- *Pr. Hui (Helen) Li, Florida State University*
  - *Power converters design modeling and optimization*
  - *Power engineering systems*

FLORIDA STATE UNIVERSITY 1851 VIRES ARTES MORES

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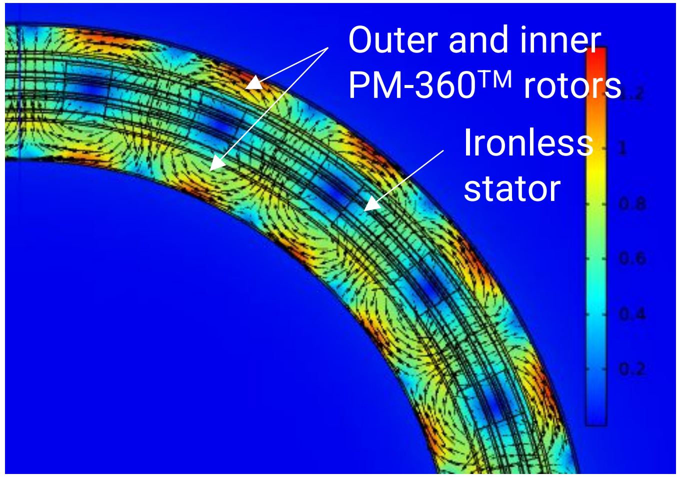
Motor Details –Innovation and Configuration

- *Dual-Rotor configuration with air-core stator winding*
  - *Dual-Rotor array system provides ideal field in the stator (high magnitude, radial)*
  - *No iron is needed in the rotor or the stator*
  - *Magnetic field is well contained in the motor*
  - *"Transparent" stator winding allowing for direct cooling*
  - *Enabling Permanent Magnet Technology*
    - *Circular PM-360™ - Continuously Changing Magnetization (Single-piece, ring and helix "Halbach Array")*

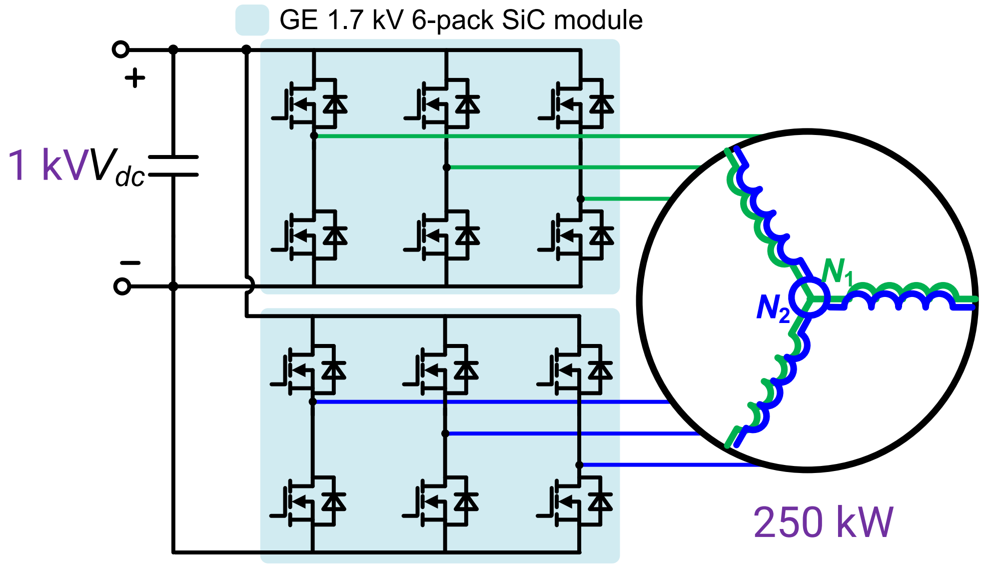
PM-360™



Metric	Units	Design Value
Take off specific power for the motor	kW/kg	26
Take off specific torque for the motor	Nm/kg	50
Motor density	kg/m3	598
Efficiency at take off	%	94.5
Take off slot current density	A/mm2	33
Active to total mass ratio	-	0.67
Structural density	kg/m3	198
Take off TRV (Peak Torque per unit rotor volume)	Nm/m3	4.92E5

Drive Details –Innovation and Configuration

- *Dual inverter configuration for redundancy, reduced dc link capacitor and fault-tolerant capability*
- *Two-level topology, 6-pack SiC modules, and optimized cold plate for high power density*
- *Proposed active gate driver for minimum switching and controlled dv/dt*



Parameters	Target Metric
Input voltage	1 kV
System capacity	250 kW
Takeoff efficiency	99.01%
Estimated overall thermal resistance	< 0.02 K/W
Switching frequency	40 kHz
Power device	1.7 kV/400A SiC

250 kW design	Weight (g)	Qty.	Total weight (g)
Power device	544	2	1088
Cold plate +adaptor +connector	1350	1	1350
Dc-link capacitor	11.5	66	760
Gate drivers	250	2	500
DSP w/ signal conditioning	400	1	400
Current sensor	97	2	194
Busbar + power terminal	300	2	600
Expected power density with cold plate: 51.1 kW/kg			

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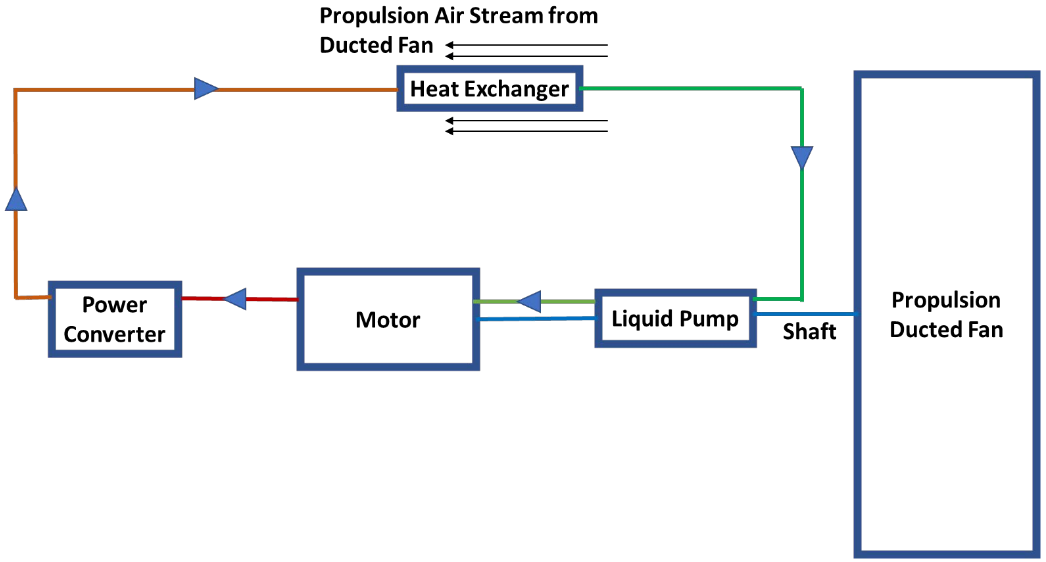
Thermal Management System Details

- *System cooling*
  - *Motor and drive **integration** (co-location) to minimize pressure drop and coolant volume*
  - ***Common** liquid cooling*
  - *Circulation achieved by impeller driven by the propulsion motor*
  - *Heat is rejected to the propulsion air stream via a finned tube heat exchanger (assuming the motor is driving a ducted fan)*
- *Motor cooling*
  - *Stator winding mounted on **"high" thermal conductivity substrate***
  - *Cooling channels allow for flow of **coolant** very **close** to the stator wires (transparent stator)*
- Drive cooling
  - ***Coolant close to** SiC **switches** for minimum thermal resistance*



Metric	Units	Design Value
TMS Coolant	-	Ethylene-Glycol and Water Mixture
TMS Mass	kg	3.83
Coolant flow rate	kg/s	0.4
Coolant Inlet Temperature	deg C	40
Overall Drivetrain Specific Power	kW/kg	13.63
Overall Drivetrain Efficiency	%	93.5%

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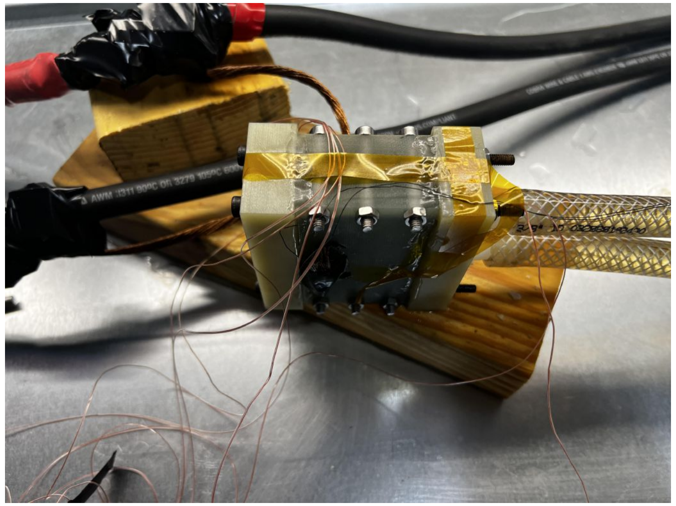
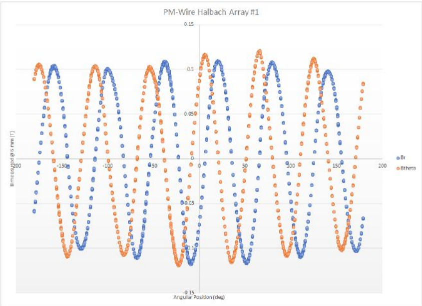
System Integration and de-risking testing

- *Drivetrain heat exchanger de-risked via numerical modelling.*
- *Stator de-risking – completed*
  - *Stator section (2 pole) fabricated and tested*
  - ***Stator peak current density of 40 A/mm^2 achieved at nominal flow rate resulted in peak temperature of 60-65 C***
    - *Stator peak temperature < 150 C*
    - *Flow rate per pole < 0.5 LPM (stator flow rate : < 24 LPM)*
    - *Pressure drop < 13.8 kPa*
  - ***Mission profile test : Peak temperature remains well below the limits throughout the flight profile** (varying current densities and flow rates)*

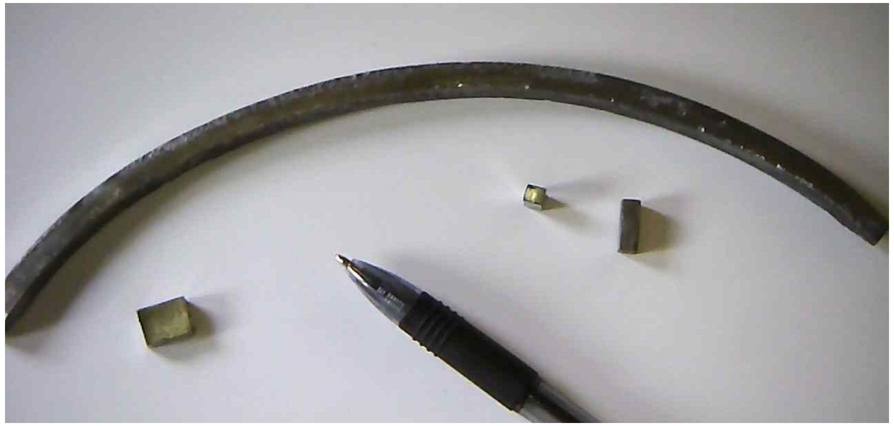


Prototype stator used for de-risking



PM-360™

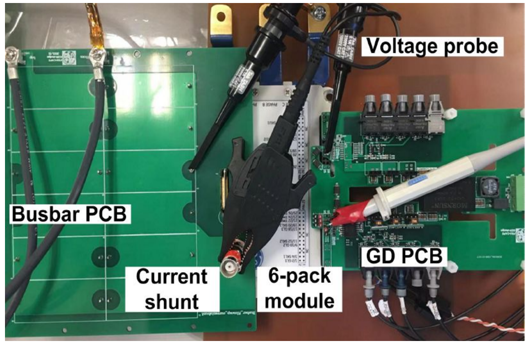
- *Sintered PM-360™ – ongoing*
  - *Ongoing challenges*
    - *Powder availability is limited to small batch sizes (100g)*

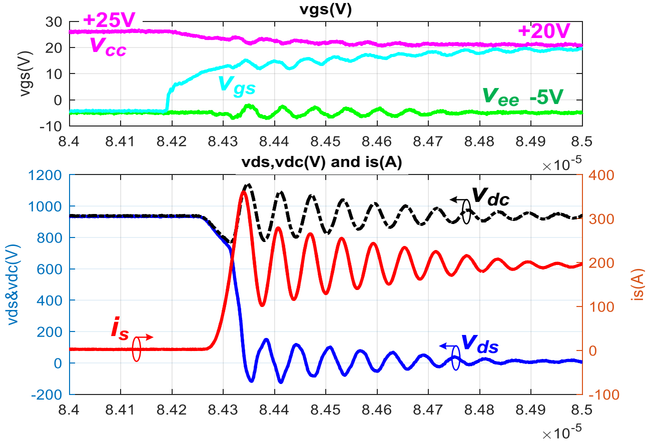


PM-Wire™ Sintered Magnet Samples

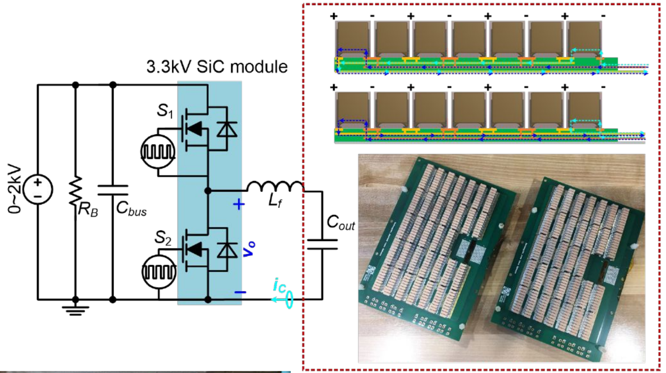
De-risking Activities

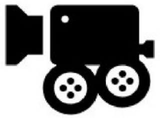
- *Switching losses reduction and verification - completed*
  - *Turn-on energy loss : 5.1 mJ @ 940V, 195 A*
  - *Switching loss < 1.7 kW*
  - *Fault protection repsonse time < 500 ns*
  - *Experiment verification: finished*



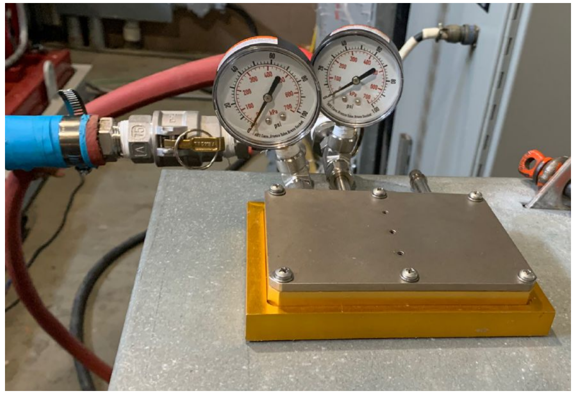


- *Dc-link capacitor cooling – ongoing*
  - *Maximum temperature < 120 C*
  - *Temperature distribution error < 10%*
  - *Status : Components purchased, and test bed built*





- *Drive Cold Plate Testing– ongoing*
  - *Maximium target baseplate temperature < 87.5 C*
  - *Maximum target flow rate < 24 LPM*
  - *Maximum target pressure drop < 80 kPa*
  - *Status : Simulation results are consistent with the above targets. Currently conducting experimental verification.*



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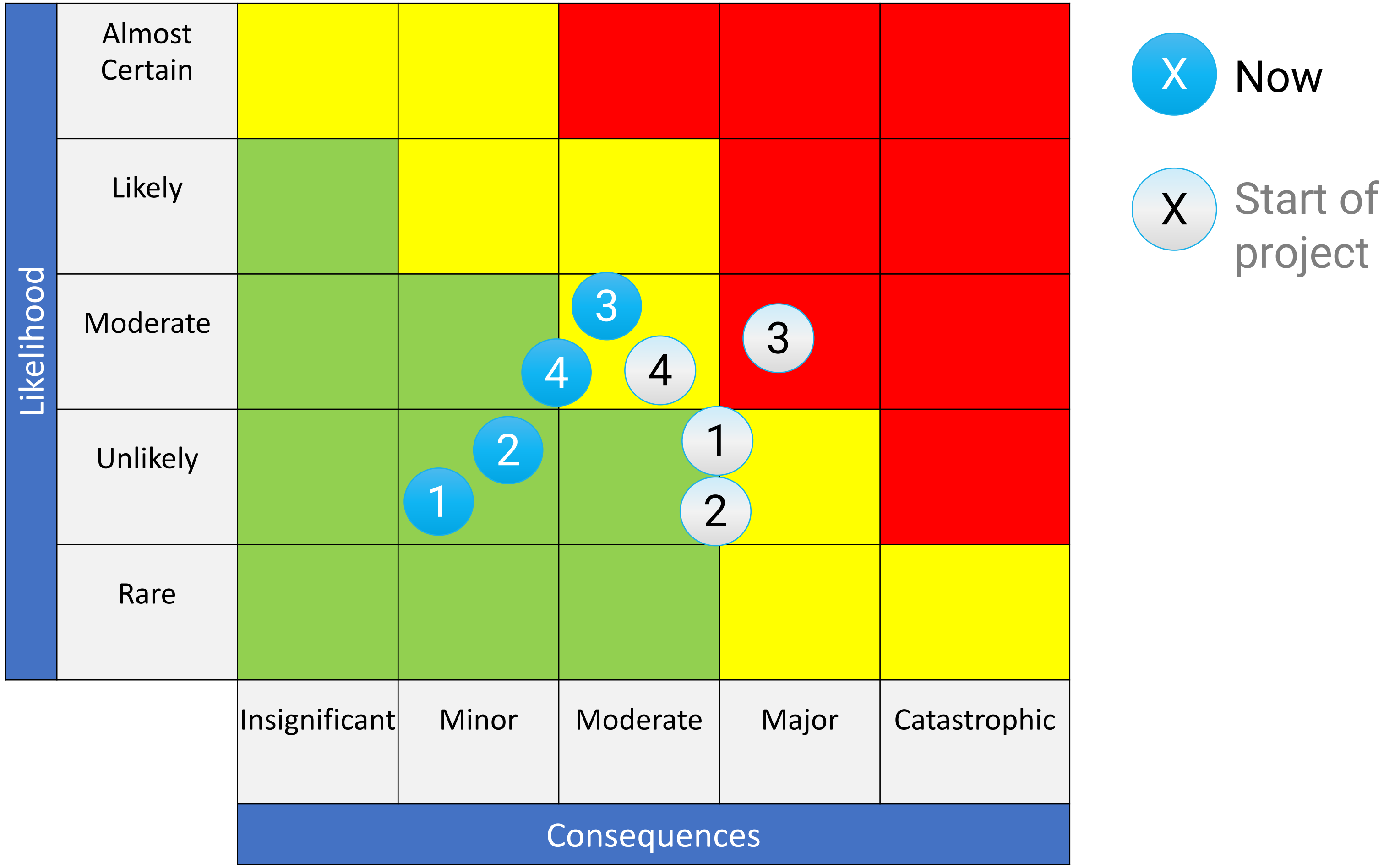
Risk Update

#	Risk
1	Stator cooling not allowing a high enough current density
2	Cooling of the power converter not allowing high enough frequency
3	Sintering of PM-360^{TM} limiting performance due to shrinkage, outgassing, alignment
4	Manufacturing tolerances of PM-360^{TM} after sintering: dimensions, concentricity, jacket thickness



Technology-to-Market Approach and Update

- *Commercialization Plan*
  - *License drivetrain to an electrical machine manufacturer*
  - *Manufacture customer specified PM-360™ magnets / rotors for electrical machine manufactures*
- *First Markets – Defense, Aircraft Propulsion, Industrial Motors*
- *Market Requirements – Innovations such as PM-360™ enable optimization of cost and performance for motor rotors*
- *Potential Aircraft/Platform* ***– Ongoing discussions with existing customers for aircraft propulsion and generation***
- *Long-term Markets – Electric Transportation, Power Tools, Medical Equipment*
- *What we have learned –* ***Strong Demand*** *based end-use application design studies with dozens of manufacturers*
- *Economic Analysis – Magnet and permanent magnet rotor/motor* ***market is large and growing exponentially***
- *Intellectual Property – One (1) Patent; Five patent applications*

Looking Ahead – What is anticipated for an Eventual Phase II?

- *Qualify a 250kW + propulsion motor for a commercial customer / application*
  - *Design, manufacturing and testing of the alignment coils for PM-360™*
  - *Manufacture and test the motor drive*
  - *Manufacture and test the permanent magnet motor*
  - *Manufacture and test the thermal management system*
  - *System integration*
  - *System testing*

- *Secure a commercial partner for developing an aircraft drivetrain and / or sub-components (e.g. motor rotor) based on a customer's applications specifications*

- *Produce / commercialize PM-360™ magnet assemblies for motor / generator applications*

Q & A

https://arpa-e.energy.gov